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EFFECT OF POSITION AND SIZE OF OPENINGS ON IN-PLANE BEHAVIOR OF UNREINFORCED MASONRY (URM) WALLS

Zhen LIU¹, Adam J CREWE²

ABSTRACT

In recent earthquakes, many masonry structures have been shown to have poor seismic performance. In particular, small to medium sized domestic structures, formed from masonry panels with openings such as doors and windows, have performed badly. Therefore, a better understanding of the impact of the openings on masonry panel performance is needed. A specific challenge is that even small windows or door openings can reduce the stiffness and strength of the masonry panels significantly, and this usually results in poor performance or collapse of the masonry structure under seismic loading. For characterizing the impact of openings in masonry panels, a series of numerical models with possible opening sizes have been studied under simulated seismic loading. This paper describes a set of parametric masonry panel models built using the code “3DEC” which is based on the Discrete Element Method (DEM). Unlike Finite Element methods, DEM allows significant displacements between the blocks to develop and new contacts are automatically recognized as part of the analysis. This analysis method is therefore able to capture the appearance of cracks, crack propagation and the failure patterns of the masonry walls. The models were created using deformable blocks for each brick along with a Coulomb-slip joint model for the mortar joints. A series of quasi-static pushover analyses have been developed looking at the impact of changing the position and size of the opening. Overall, this paper describes how the masonry walls were modelled, the calibration of the numerical models and the analytical results from the parametric studies. A good agreement between this numerical model and data from previous papers results was achieved, verifying the reliability and robustness of this approach. The relationships between the size and position of the opening in the panel and seismic performance of panel are described and discussed.

Keywords: Unreinforced Masonry Walls; Opening effects; Discrete element method; 3DEC; Quasi-static analysis

1. INTRODUCTION

Low-rise masonry buildings are built all over the world, especially in rural areas, the majority of these being unreinforced masonry (URM). Low-rise masonry structures and, in particular, URM buildings have exhibited poor seismic performance in recent earthquakes and the size and position of openings have been demonstrated to have a significant impact on the extent of damage (Parisi et al. 2013). Openings reduce the stiffness of masonry structures and can even change the failure mechanisms of masonry panels. Some relevant experiments summarized by Mohammadi and Nikfar (2012) have evaluated the relationship between stiffness reduction and the opening percentage for the masonry infilled panels. This research has illustrated that the stiffness reduction in a structure can be directly related to the percentage of openings in the structure. In addition, the layout of openings has an influence on the distribution of gravity loads which results in concentration of strength and drift demands in some parts of the structure, which has the potential to increase the vulnerability of masonry walls under seismic loading (Parisi et al. 2013). However, little research has considered impacts of both opening position and the percentage of openings on the seismic performance of URM. This paper aims to identify the relationship between the effects of both opening position and percentage on the seismic capacity of masonry panels.

¹PhD candidate, University of Bristol, Bristol, United Kingdom, zl15471@bristol.ac.uk

²Reader, Civil Engineering, University of Bristol, Bristol, United Kingdom, A.J.Crewe@bristol.ac.uk

A Discrete Element Method (DEM) is used to model the masonry panels and relevant numerical models are built in 3DEC software. The methodology for setting up the analytical methods and for creating the models with different opening size and position under in-plane behavior is presented. Calibration of numerical models against previous experimental work is also carried out to verify the reliability of the modelling technique. Finally, the relationships between the opening size and location and the seismic performance of the walls are presented considering the potential failure patterns induced by the openings. This work will be of interest when considering the impact of openings in URM during seismic assessment and design procedures.

2. OVERVIEW OF DEM AND 3DEC FOR MASONRY MODELLING

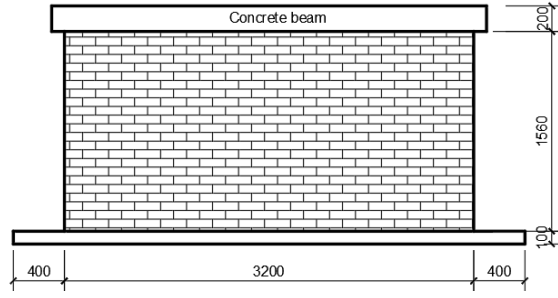
The Discrete Element Method (DEM) method was firstly proposed by Cundall (1971) as a numerical method for analyzing a blocky rock system. According to Lemos (2007), the DEM relies on the assumption that the structure being modelled can be regarded as an assembly of distinct bodies, such as masonry units that only interact along their boundaries. De Felice (2011) explored the out-of-plane seismic capacity of masonry walls depending on wall section morphology, this paper provided detailed methods for defining the failure criterion in 3DEC under quasi-static response, the results showing the extent to which the wall could fail based on a rigid body motion or, conversely, fail due to breaking of the external leaf. Similarly, Lemos and Campos (2017) simulated shaking table tests of masonry buildings under out-of-plane behavior. That paper covered both quasi-static and dynamic problems, and it was shown that the DEM reproduced the most significant features of the shaking table tests. Bui et al. (2017) developed a 3D DEM numerical model to study the in-plane and out-of-plane behavior of dry-joint masonry wall constructions. That article simulated the collapse patterns for comparison with experimental data and obtained similar failure mechanisms for the masonry panels. An example comparing 3DEC analyses with experimental data for plain and reinforced masonry walls can be found in Luiza et al. (2018).

3DEC is software based on the UDEC code (Universal Distinct Element Code) and it has been applied in many different analysis areas. The 3DEC code is based on DEM theory and more details can be found in Itasca (2012). In 3DEC, the representations of contact and block are similar to standard DEM method and the blocks can be described as rigid or as deformable. A rigid block does not change shape even under applied loading, while deformable blocks are sub-divided into triangular elements, which are based on FE method, and these allow calculation of deformation of the blocks. The main difference between 3DEC and a normal FE model is the fact that in 3DEC models only the blocks need to be meshed and the joints are generated automatically as additional blocks are added, as compared to FE where all the contact elements need to be specifically defined. In 3DEC, the mortar joints are built as zero-thickness interfaces and are represented by point contacts rather joint elements, these points can be used to identify the stresses and displacements across the joint.

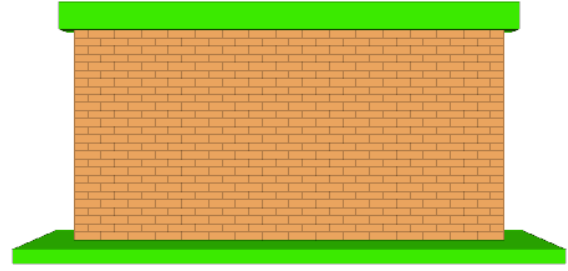
3. METHODOLOGY OF MASONRY PANEL MODELLING WITH 3DEC

3.1 Geometry

The geometric models of the masonry panels were built in 3DEC. The size of each masonry block was set as 0.06m x 0.2m x 0.1m (height x span x breadth), and the dimensions of masonry panels were 3.2m x 0.1m x 1.56m (length x width x height). Under the masonry panel, a block was created to represent the ground and an embedded concrete beam with a size of 3.4m x 0.2m x 0.2m (length x width x height) was located at the top of masonry panel where vertical loads would be applied. The detailed geometry of the models is shown in Figure 1.



(a) Schematic diagram of the numerical model



(b) Numerical model in 3DEC

Figure 1. Geometry of numerical model in 3DEC

3.2 Models of block and joint

Four basic constitutive models for blocks exist in 3DEC: the null model; an elastic isotropic model; an elastic anisotropic model and a Mohr-Coulomb plasticity model (Itasca. 2012). The null model means that the material for any blocks built with this model is removed or excavated and the stress in the block is set to zero. The elastic, isotropic model is the simplest material model and reflects a material behavior that is isotropic and continuous and can be represented by a linear stress-strain behavior following Hooke's law, without hysteresis on unloading. This material model is used in this paper because the main panel failure usually occurs along the joints (Sarhosis et al. 2015) and (Halabian et al. 2014) rather than through the blocks. Input material parameters for the elastic material model are density, Poisson's ratio, elastic modulus (E) or bulk modulus (K), and shear modulus (G).

In these 3DEC simulations, the joints between the blocks were presented by a zero-thickness interface between the adjacent blocks, as mentioned in Section 2. Along the interfaces, contacts are defined based on a number of potential contact points. These contact points are defined at the edges or corners of the blocks and they are connected by two assumed springs such that they can transfer normal and shear forces between the blocks. A coulomb-slip joint model is the basic constitutive model employed in 3DEC, and all the sub-contacts between the blocks follow the Coulomb friction rules; with shear failure, tensile failure and joint dilation all being modelled. In the elastic range, the behavior is governed by the joint stiffness and shear stiffness, and during the plastic stage, the behavior is controlled by the tensile strength, cohesion, frictional angle and dilatation angle. The material parameters adopted for this work can be seen in Table 1 and Table 2 adopted from (Candeias et al. 2017) and (Lemos et al. 2017).

Table 1. Properties of masonry blocks.

Density [kg/m ³]	Young modulus [N/m ²]	Poisson's ratio [-]
1890	5.17E10	0.15

Table 2. Properties of joints.

Joint normal stiffness [N/m ³]	Joint shear stiffness [N/m ³]	Joint friction angle [Degrees]	Joint tensile strength [N/m ²]	Joint cohesion
1.74E10	8.68E9	35	2E5	1E5

3.3 Quasi-static analysis and failure criterion

3DEC analysis is based on a time domain integration method that determines the equations of motion for both the rigid and the deformable blocks using an explicit finite difference method (Itasca 2012). A solution scheme based on the equations of motion calculates the potential failure modes of discontinuous

systems better than schemes that disregard velocities and inertial forces. At each timestep, the laws of motion and the constitutive equations are applied. As described by Code (2005), two load patterns are applicable for seismic analysis, namely: 1) a “uniform” pattern, based on lateral forces which are proportional to mass regardless of elevation within the structure (uniform response acceleration); 2) a “modal” pattern, where lateral forces consistent with the lateral displacement distribution, in the direction under consideration, are determined in elastic analysis using a lateral force method or a modal response spectrum analysis.

As the 3DEC software has not yet implemented a “modal” loading pattern, a uniform response acceleration was applied to perform pushover-type tests. First, the base block was fixed and vertical gravity load was applied, then a uniform horizontal acceleration was applied to the masonry panels, in increments of constant value, until the failure took place. To determine the failure load, the relationship between load steps and the horizontal displacements needed to be monitored carefully. Under this type of load controlled analysis, once failure took place the horizontal displacement would increase dramatically. Therefore, the displacement at each load step was calculated and ultimate capacity of the wall was then based on the flattening of this acceleration / displacement curve.

3.4 Calibration of numerical models

To check the validity of the numerical models in 3DEC, a model of a simple dry-jointed masonry wall was built and was subjected to combined shear and vertical pre-compression loads to compare the failure patterns with published experimental data (Lourenço et al. 2005). The size of all the masonry panels was 1000mm x 1000mm x 200mm (height x span x breadth) and the blocks were 100mm x 200mm x 200mm (height x span x breadth) in dimension. The density of block was 2200 kg/m³, the Young's modulus of blocks was 15500 N/ mm² and the Poisson's ratio was 0.2. The joint properties were determined by (Bui et al. 2017). The comparison of failure pattern is shown in Figure 2.

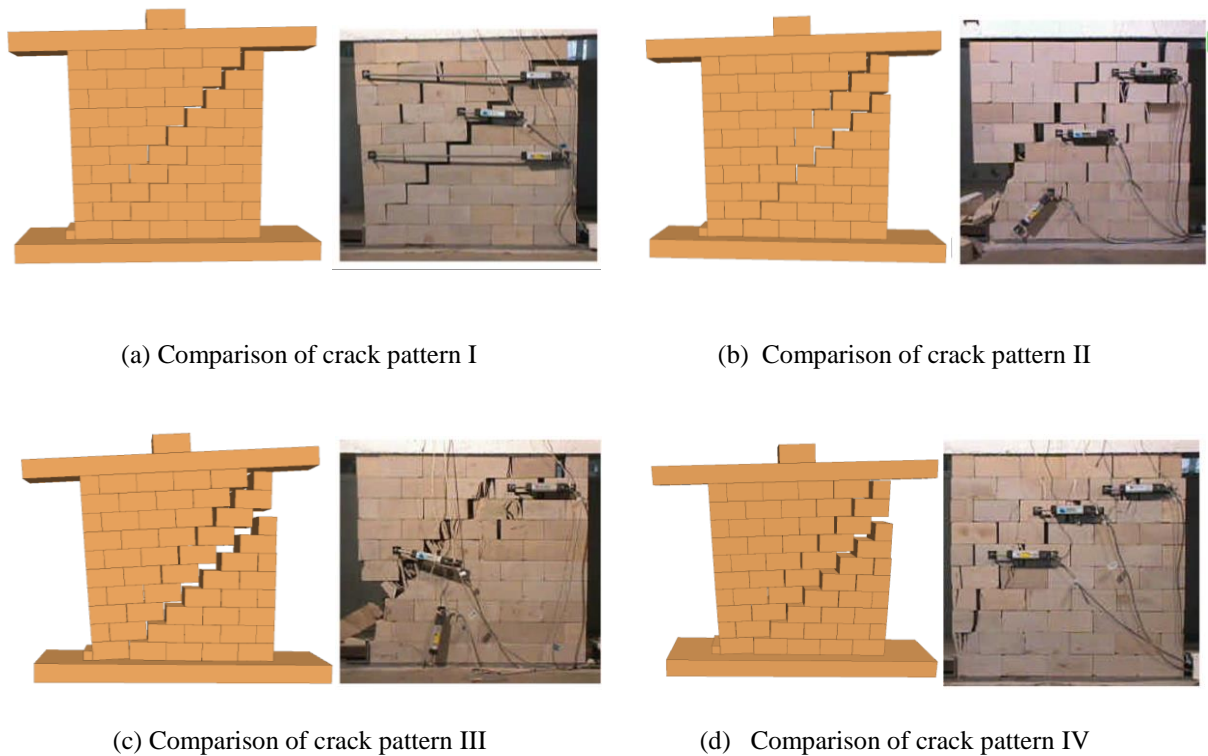


Figure 2. Crack pattern comparison: Numerical models and experiment data (With permission from ASCE)

Comparing the crack patterns between the numerical and the experimental data, it can be seen that the numerical models built in 3DEC show a similar crack pattern to the experiments (Bui et al. 2017). The main failure modes in the 3DEC model are the de-bonding of the top concrete beam and a diagonal

crack, which are very similar to the experimental results. It is notable that, due to the linear elastic assumption made for the block material, the numerical models could not simulate any crushing failure in the experiments. Nevertheless, it can be seen that the numerical models can successfully simulate quasi-static response of masonry walls under in-plane loading.

4. OPENING PERCENTAGE EFFECTS UNDER IN-PLANE BEHAVIOR

3DEC models were built to identify the effect of the percentage of opening in a wall panel. The masonry panels without an opening and with different percentages of openings are shown in Figure 1 and Figure 3. The opening sizes were divided into 8 cases, identified as OS1 to OS8, and detailed information about the sizes of openings can be seen in the table to the right of Figure 3. The material properties of the masonry panels were as given in Table 1 and Table 2. With respect to the applied loading, first, vertical gravity loads and then a 100kN vertical load (to represent a floor or roof load) was applied on the top of concrete beam. Then horizontal gravity loads, in increments of 0.01g, along the positive X direction were applied until collapse took place. The horizontal displacement of the top-right brick was monitored to calculate the displacement for the acceleration/displacement curves.

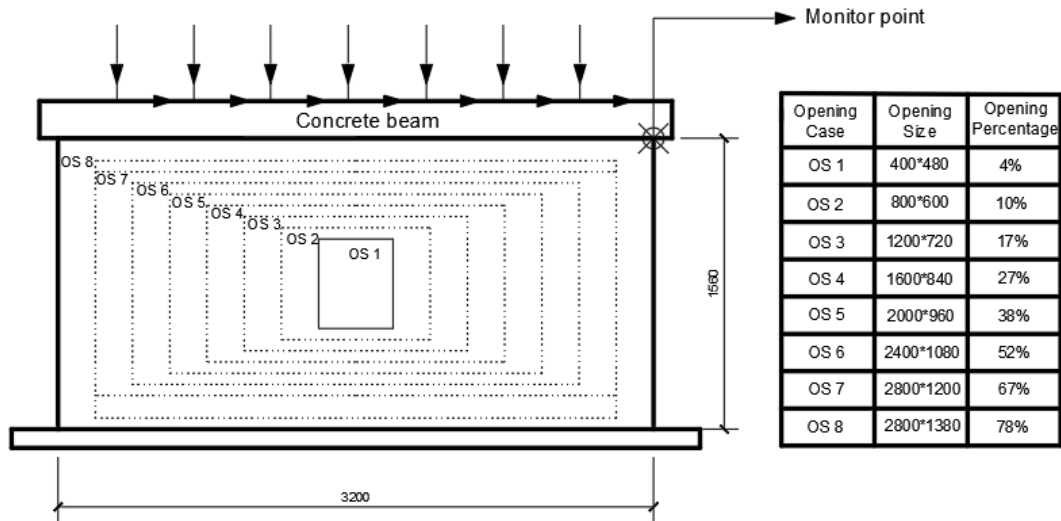


Figure 3. Different opening sizes of masonry panels

The acceleration/displacement curves for different opening percentages is given in Figure 4.

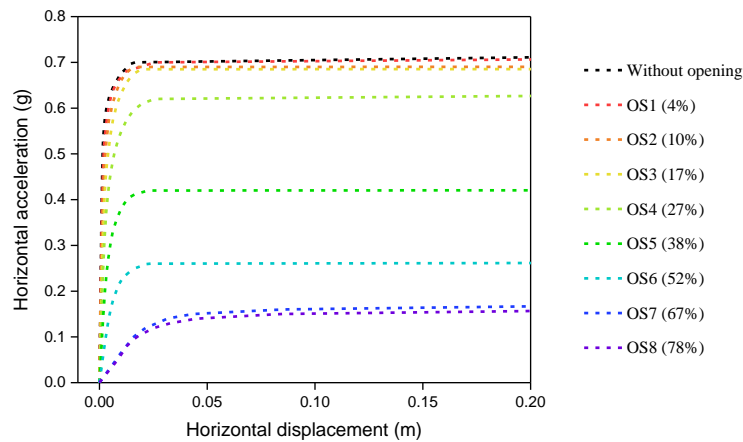


Figure 4. The pushover curve for different opening sizes of masonry panels

It can be seen that the walls with small openings, OS1, OS2 and OS3 (4%, 10% and 17%), all behave

in a similar way and resist maximum horizontal accelerations which are very similar to the masonry panel without opening. However, there is a change in panel behaviour when the opening size becomes 27% of the panel (OS4). When the opening size becomes 37% of the panel (OS5) there is a dramatic change in panel behaviour and the wall now only resists 60% of the load of the intact panel.

For OS 7 and OS 8, both panels show similar low values maximum acceleration resistance. Figure 4 demonstrates that the seismic capacity begins to decrease significantly when an opening of more than 27% of the wall is incorporated into the panel. Once opening percentage becomes more than 70%, the seismic capacity does not change significantly, mainly because the strength is already so low and the wall starts to behavior more like two independent masonry columns. Figure 5 shows the relationship between the opening percentage and the maximum horizontal acceleration for the in-plane strength capacity of the masonry panels.

It is obvious that the maximum acceleration is relatively constant for opening percentages under 15%; for the range of 15%~65%, the in-plane strength capacity drops dramatically following a roughly linear trend; and for higher opening sizes the residual strength is fairly constant. The wall capacities could therefore be classified in three phases. Phase One, 0%~15% opening percentage, the wall strength is essentially the same as for a wall with no opening; Phase Two, 15%~65% opening percentage, the in-plane strength of the wall decreases as the opening percentage increases; Phase Three, greater than 65% opening percentage, the strength capacity is about 10% of the value of the intact wall with no openings.

It is notable that, with the application of a large vertical load in this particular analysis, the masonry panels with small openings have a similar seismic capacity to that of the masonry panel without opening. However, this may not be the case for other vertical load values and further research into the effects of vertical loads need to be considered in the future. The collapse patterns for the walls with different opening percentages are given in Figure 6. Looking at the failure patterns of the different masonry panels, it can be seen that most of the cracks form through the openings. OS1, OS2 and OS3 show a similar crack pattern with a single main crack running diagonally from top left to bottom right of the walls while for OS4, OS5 and OS6 cracks are generated along both diagonal directions. For OS7 and OS8, the opening is so large that the in-plane behavior of both structures follows a similar pattern to that of a frame structure.

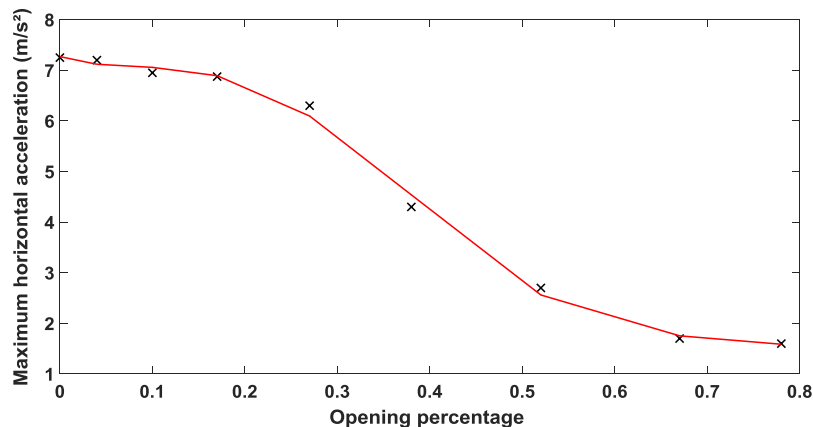
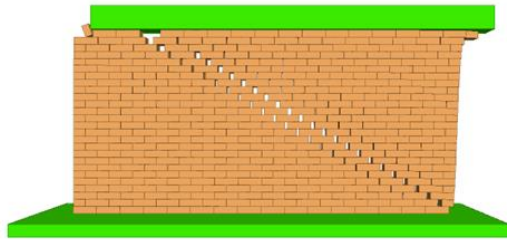
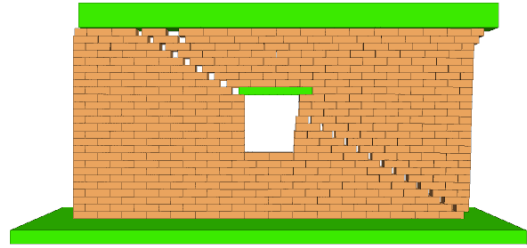


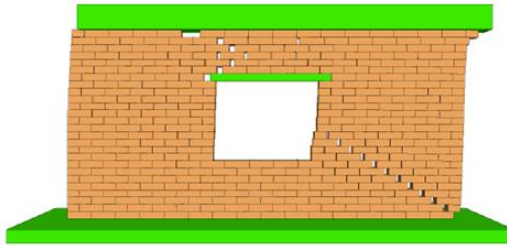
Figure 5. The relationship between the opening percentage and the in-plane capacity



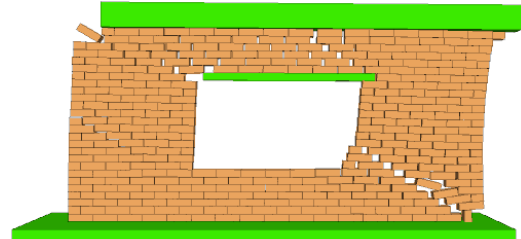
(a) The masonry panel without opening



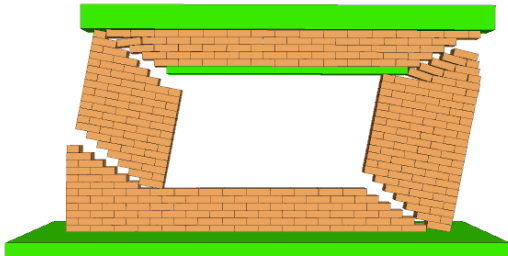
(b) The masonry panel with opening OS 1



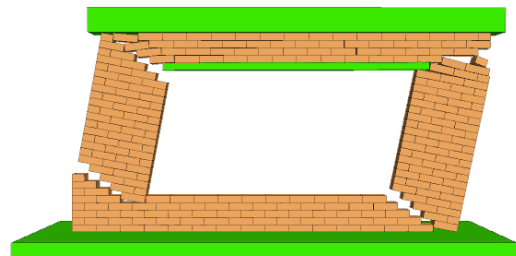
(c) The masonry panel with opening OS2



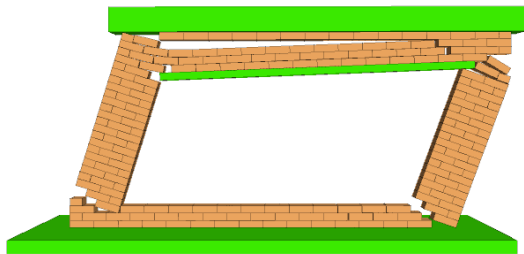
(d) The masonry panel with opening OS 3



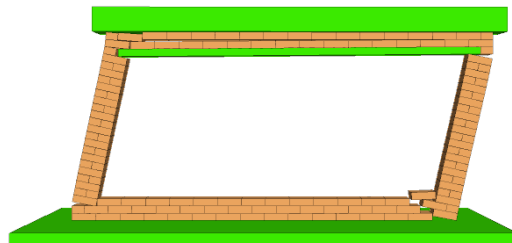
(e) The masonry panel with opening OS4



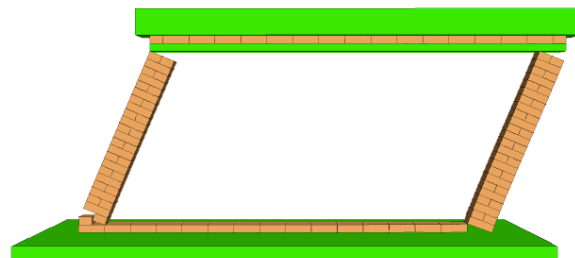
(f) The masonry panel with opening OS 5



(g) The masonry panel with opening OS6



(h) The masonry panel with opening OS 7



(i) The masonry panel with opening OS 8

Figure 6. The in-plane collapse patterns of the different masonry panels under lateral gravity loading

5. OPENING POSITION EFFECTS UNDER IN-PLANE BEHAVIOR

A similar in-plane set of tests to those described in section 4 was performed in 3DEC to evaluate the effect of the opening position on masonry panel performance. The definition of opening position was taken as the position of the centre of the opening in the wall. A total of 66 opening points were considered in a grid of 11 points along the horizontal direction by 6 points in the vertical direction. The 66 points, spaced horizontally by 200mm and vertically by 180mm, were labelled A1 to F11 as shown on Figure 7. The opening size for this study was assumed to be 1m×0.54m which represents an opening percentage of approximate 11%. The opening locations for all 66 analyses are shown in Figure 7.

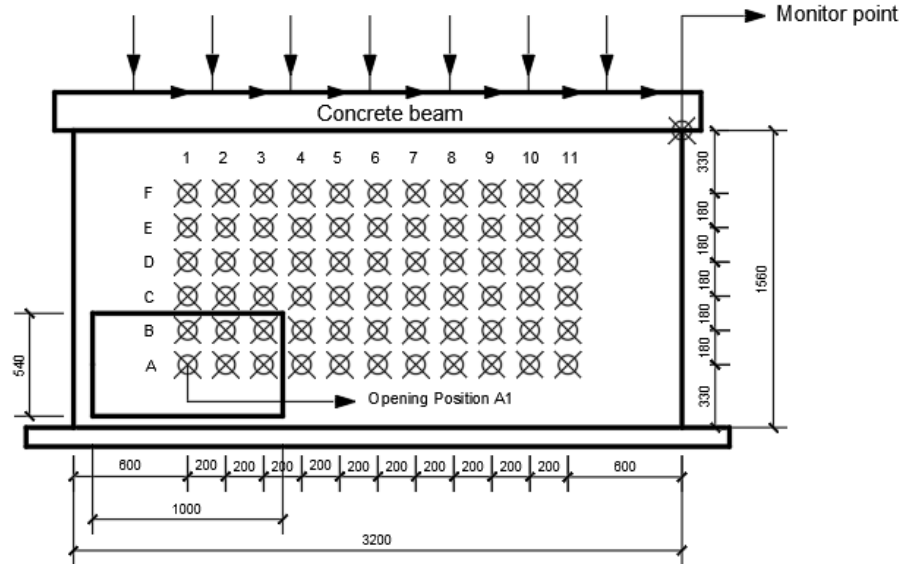


Figure 7. Different opening positions of masonry panels

The peak horizontal acceleration at failure for each of the opening positions is shown Figure 8. Figure 8 shows that the location of the opening in the masonry panel has a significant effect on the maximum horizontal acceleration at failure, with the failure acceleration ranging from 0.58 to 0.715g. With the opening in the middle part of masonry panel, the accelerations required for failure remain relatively stable and have higher values compared to when the opening is on either side of the panel. An opening in the right side of the masonry panel also exhibits worse in-plane behaviour performance than an opening in the left side. An explanation for this is that when the opening is on either side of the panel this creates an imbalance in the numbers of the bricks around the opening which is more likely to result in a more localised failure, resulting in a lower in-plane capacity compared to when the opening is more symmetrically in the middle of the panel.

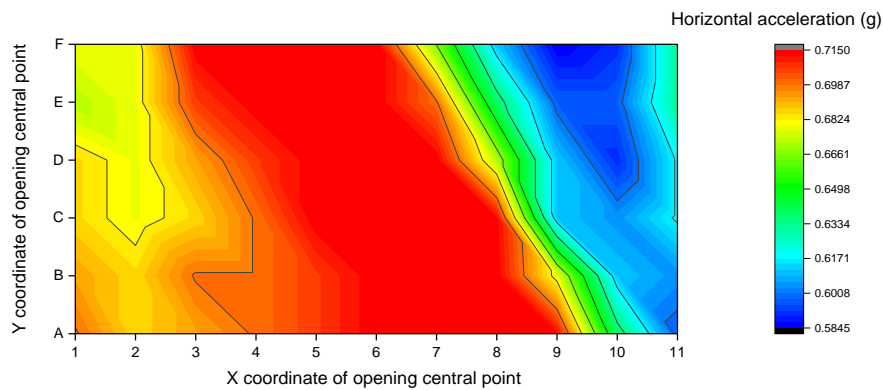
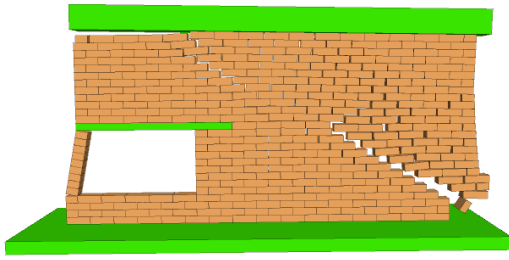
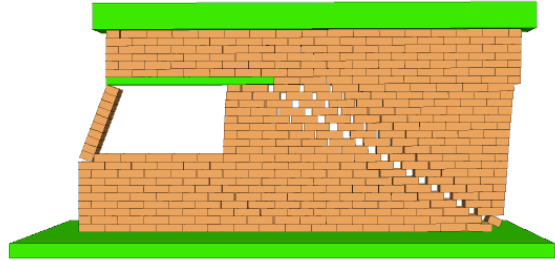


Figure 8. The in-plane strength capacity of the masonry panel with the opening in different positions

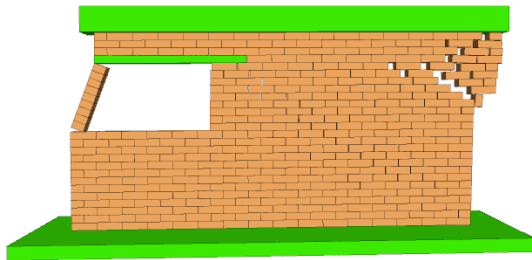
The failure mechanisms of a selection of the 66 masonry panels analyzed for different opening positions are given in Figure 9.



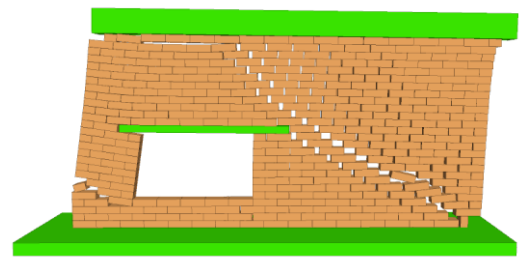
(a) The masonry panel without opening position B1



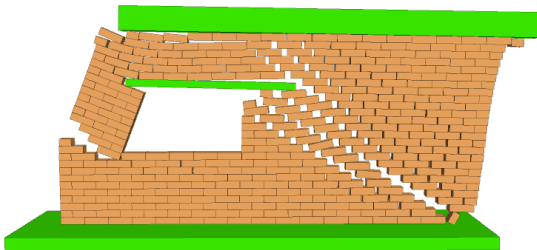
(b) The masonry panel with opening position D1



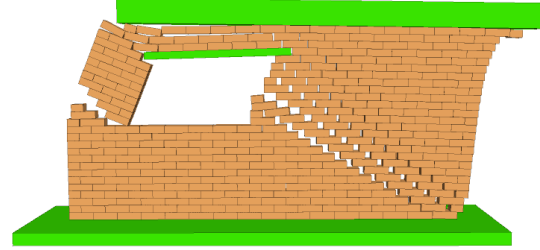
(c) The masonry panel without opening position F1



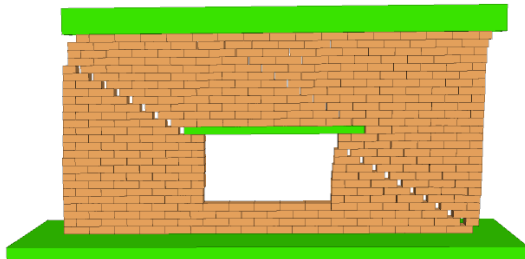
(d) The masonry panel with opening position B3



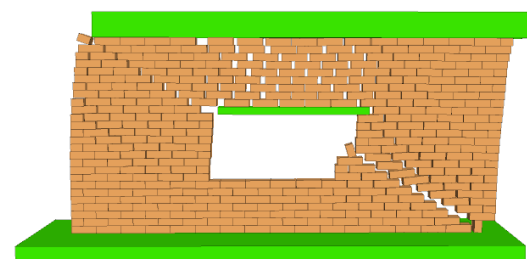
(e) The masonry panel without opening position D3



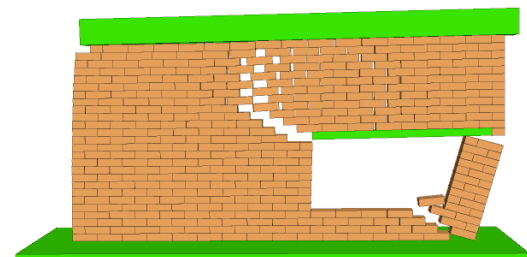
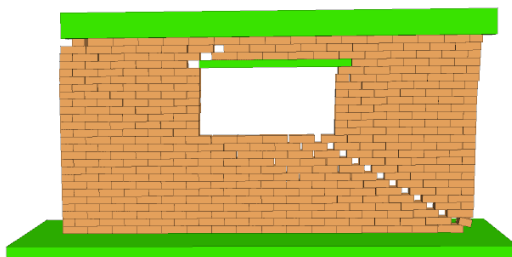
(f) The masonry panel with opening position F3



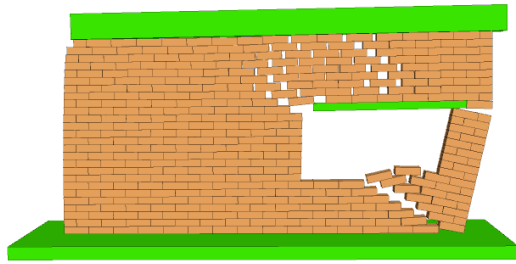
(g) The masonry panel without opening position B6



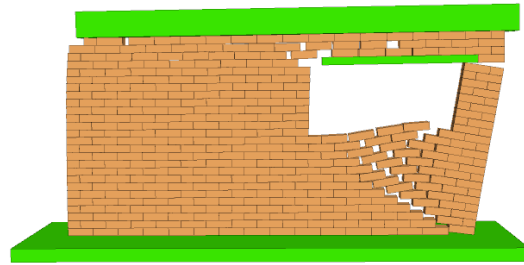
(h) The masonry panel with opening position D6



(i) The masonry panel without opening position F6



(j) The masonry panel with opening position B10



(k) The masonry panel without opening position D10

(l) The masonry panel with opening position F10

Figure 9. Failure mechanisms of masonry panels under in-plane load

Looking at the failure mechanism of masonry panels in Figure 9 it is obvious that when the opening is on the right-hand side of the panel fewer bricks are mobilized in resisting the horizontal load, and this quickly leads to larger local displacements and failure of the wall. When the opening is in the middle of the wall the cracks generally form diagonally through the opening, whereas when the opening is at the edge of the panel more localized failures occur in the masonry. Based on these results it is therefore unwise to allow openings too near the edges of a masonry panel. It can be seen that the changing the position of the opening affects the failure mechanisms of masonry panels under in-plane behavior, and the associated cracking patterns.

6. CONCLUSIONS

This paper has identified the effects of opening sizes and positions on the seismic performance of masonry panels subjected to in-plane loading. Even though the blocks were assumed to be elastic in the analyses it can be seen that 3DEC can simulate the quasi-static response successfully, and in particular is able to describe the progress of interaction between the blocks and joints. The relationship between the opening size and performance of masonry panels has been evaluated, for a range of opening percentages from 15% to 70% and an opening size of more than about 20% of the panel starts to affect the panel performance. The position of the opening also has an effect on the wall behavior and, for the panel being considered, positioning the opening near the edges of the wall reduced the load capacity by about 20%. The direction of applied loading also needs to be considered when evaluating failure patterns for in-plane behavior. Only a small range of the parameter space has been presented in this paper. Further sensitivities studies are needed, as is more research looking at the influence of openings in panels with different height-length ratios, different vertical loads, fully confined panels, out-of-plane behavior and dynamic behavior.

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